MODELING OF SUSTAINABLE HYDROGEN PRODUCTION / STORAGE ENERGY SYSTEMS FOR REMOTE APPLICATIONS

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ABSTRACT

The results from computer simulation of an integrated renewable hydrogen energy system with daily and seasonal energy storage are reported in this paper. The main components of the energy system are a photovoltaic array, PEM electrolyzer, PEM fuel cell, battery, pressurized hydrogen storage unit, controller, and electric load. The modeling was performed using modified TRNSYS simulation software. System size, performance, and cost trade-offs were analyzed by simulating two short-term energy storage scenarios: one with a large battery storage capacity (approximately one day) and one with a much smaller capacity (two hours). Results show that a system with a small battery storage capacity is more desirable in the interest of system renewability, however it is more capital cost intensive.

INTRODUCTION

The concept of stand-alone renewable energy systems that use hydrogen as an energy storage medium has attracted much attention recently. The main objective of this work is to develop an efficient tool to assist in the design and evaluation of integrated solar hydrogen production/storage energy systems (ISHES). We have conducted an extensive literature search on different ISHES demonstration projects and the existing computer simulation software packages (CSP) (for example, references [1-5]).

In the simulation of the ISHES, batteries are included for short-term storage of electricity generated by the photovoltaic (PV) array and the fuel cell. In the interest of keeping the ISHES system as renewable as possible, it is desirable to utilize as few batteries as possible in the system design. Batteries tend to have a much shorter lifetime (5-10 years) compared to the renewable sources of electricity found in the system (20 years). However, as the amount of battery storage capacity decreases, the sizes of other system components, such as hydrogen storage capacity and size of the PV array, increase in order to compensate. In order to investigate this system trade-off, two simulation studies have been conducted on the proposed ISHES. Case 1 has a large battery storage capacity (approximately one day) and Case 2 has a much smaller capacity (two hours).

METHODS

We chose the TRNSYS simulation package, created by the Solar Energy Laboratory (SEL) at the University of Wisconsin-Madison, to be the main platform for the system integration and simulation [6]. TRNSYS is transient simulation software with source code written in FORTRAN. No models for the core components of the ISHES (fuel cell, electrolyzer, and hydrogen storage) are currently included with the standard version of the TRNSYS software. However, the SEL has collected many applicable component models, written by various users, and currently uses them to demonstrate the capabilities of the software.

The following paragraphs outline individual component specifications used in the simulation. These specifications have been optimized such that the renewable energy system can meet the load requirements with zero percent system downtime. The length of each simulation was one year, beginning in January and ending in December.

Location/Weather Conditions. Typical meteorological year (TMY) data which includes average values for solar insolation, ambient temperature, and humidity for Orlando, FL (28° N) has been used as a starting point for the simulation.

Load Profile. The peak load each day is 10 kW, which occurs in the early evening, and the daily average load is 2.5 kW. The daily, peak, and average loads that the ISHES system must supply also take into account losses encountered in AC/DC power inversion, DC/DC voltage conversion, and power requirements of various system components (i.e. controller).

Batteries. Case 1 includes a total of four deep cycle solar batteries. The batteries are connected in series, which maintains a battery bus voltage of 48 V. The battery string has a capacity of 125

Ah, which permits the batteries to store 2 hours of required system amperage based on a daily consumption of 58 kWh. Case 1 represents a situation where the batteries are only able to supply the system load when electricity production switches between the PV array and the fuel cell. No means of safety back-up power is provided in the event that the PV array and fuel cell become inoperable.

Case 2 include a total of 12 batteries arranged in an array of three parallel strings of four batteries each. In this case, each parallel string has a capacity of 635 Ah. With 1905 Ah total storage capacity, the battery array has the ability to solely power the load for 1.25 days, based on 58 kWh daily consumption. This scenario provides some back up power in the event that system interruptions are encountered with the PV array or fuel cell. Also, in this case, the size of the battery array prevents the need for the fuel cell to be solely responsible for powering the load every evening, when the PV array is inactive. Instead, the fuel cell is only required to supply power when the battery state-of-charge drops below a certain "safe" limit, caused by consecutive days of low solar insolation.

Photovoltaic Array. For case 1, a total of 588 individual modules are used in the simulation, and the array is configured with 147 parallel strings of 4 modules each. Each module is assumed to be rated at 100 W at standard test conditions (irradiance = 1000 W/m^2, cell temperature = 25 °C), therefore the peak power output of the array is expected to be 58.8 kW. The panels are tilted at an angle of 45° (28° + 17°), which optimizes electricity production during the winter months, due to the sun's wintertime position in the sky.

For case 2, a total of 256 of the same modules are used, and the array is configured with 64 parallel strings of 4 modules each. The panels are also tilted at an angle of 45°, and the peak output of the array at standard test conditions is expected to be 25.6 kW.

Electrolyzer. For these simulations, data for a high pressure (1000 psi) PEM type electrolyzer has been used in place of the alkaline data that was provided along with the TRNSYS subroutine. The PEM electrolyzer has a total of 25 cells and each cell is assumed to have an area of 279 cm^2. The electrolyzer operates at an efficiency of approximately 75%, producing approximately 0.48 kg/h (90 slpm) of hydrogen at 500 A.

Hydrogen Storage. A pressurized tank is included in these simulations that stores hydrogen as it is produced by the electrolyzer. The maximum pressure of the tank is 1000 psi. For case 1, an optimized storage volume of 20 m^3 is used in the simulation, allowing a maximum of 90 kg of hydrogen to be stored at ambient (25 °C) temperatures. For case 2, an optimized storage volume of 10 m^3 is used, allowing a maximum of 45 kg of hydrogen to be stored at 25 °C.

Fuel Cell. The PEM fuel cell used in these simulations operates on hydrogen and air and contains a total of 50 cells. Each cell has an area of 300 cm^2. The stack produces a total of 11.6 kW of DC power at 32 V and 363 A. The stack operates at an efficiency of 44% consuming 0.683 kg/h (127 slpm) of hydrogen.

Power Conditioning. In the ISHES simulation, four power conditioning devices are included. A maximum power point tracker (MPPT) maintains optimum performance of the PV panels by ensuring that the array operates at the maximum power point on its I-V curve. A DC to DC converter upgrades the fuel cell output voltage to the battery bus voltage. A diode prevents the back flow of current from the battery array and fuel cell to the electrolyzer. This ensures that the only source of power for the electrolyzer is the PV array. Finally, a DC to AC inverter is included to invert the DC power supplied by the battery array to AC power required by the electric consumer. The efficiency of all power conditioning devices is assumed to be approximately 90%.

Controller. A single controller device oversees total system operation in the ISHES simulation. By assessing the requirements and/or output available of every system component, including the electric load, the controller makes appropriate decisions to optimize system performance. These decisions include whether to connect or disconnect individual components to/from the system and whether power generated by the PV array is sent to the electrolyzer, for hydrogen generation, or to the battery array, for use by the electric consumer. The controller also decides whether the battery array contains sufficient charge to power the load under dark conditions, or whether the fuel cell should be activated to power the load and recharge the battery.

RESULTS AND DISCUSSION

Figures 1 and 2 show simulation results for case 1 and 2 respectively. In these graphs, the dark solid line shows seasonal variations (shown on the top axis) of the amount of hydrogen stored in the pressurized tank. This amount is expressed as a fraction of the total storage capacity of the tank (shown on the left axis). All remaining plots on these graphs were created using the bottom axis to show daily variations.

The power required by the load and the power produced by the PV array are shown as dashed lines on these graphs. This data has been plotted for a simulated first week of February, occurring during the simulation year. The month of February represents a "worst case" scenario, for it is expected to be the month with the lowest average solar insolation. The values are read off of the right hand axis in units of watts (please note that the power produced by the PV array in case 1 has been divided by a factor of 2 such that it can be plotted on the same graph as the load).

Finally, the battery state of charge (SOC) is shown on these graphs as a dotted line. Similar to fractional hydrogen storage, battery SOC is expressed as a fraction of the total battery storage capacity. This plot has also been created for the first week of February, and its value is read off of the left axis.

Along with the design of each individual ISHES component, total system operation plays a major role in system performance, size, and cost. Each of the individual components are intimately linked together in some way, therefore changing the size or operational parameters of one component has the potential to disturb the balance of the entire system. Simulations of the proposed ISHES have been conducted with the intent of optimizing system performance, rather than cost, however it is expected that an optimized system will also be the most cost effective. The primary parameter that is intended to be the basis for optimization is the value for hydrogen storage. Other mandatory system criteria included use of a PEM type fuel cell and electrolyzer, maximizing battery lifetime, and maintaining zero percent system downtime.

As seen in Figure 1 and 2, fluctuations in battery SOC occur according to the relative size of the battery array. With a small battery array, as in case 1, SOC decreases rapidly under dark conditions. Upon reaching a lower limit, chosen to prevent excessive battery discharge, the fuel cell is activated to recharge the battery as well as power the load. With a larger battery array, as in case 2, the fuel cell is activated less often under dark conditions, due to the slower rate of battery array discharge.

Optimizing the PV array for wintertime performance maximizes the use of the fuel cell, which represents mainly a capital expense. By also requiring fuel cell activation during the summer months, when solar insolation is the greatest and the fuel cell ordinarily may not be needed depending on the battery array capacity, this expensive piece of equipment is used to its fullest extent rather than allowing it to lye dormant for several months.

The same fuel cell has been simulated in both case 1 and 2, and the frequency of its activation affects overall system cost. As seen by the results of simulations for case 1 and case 2, a system trade-off exists among battery array storage capacity, hydrogen tank storage capacity, and the size of the PV array. As previously discussed, the fuel cell is activated more often in case 1 due to the smaller battery array storage capacity. This case utilizes more hydrogen over the course of the year and subsequently requires a hydrogen storage tank that is twice the size of the tank in case 2 (see METHODS section). This is due to the fact that with a smaller battery array, less energy can be stored in that short-term medium. Since the same amount of energy is required in each case, more energy must be stored in the form of hydrogen. Since the values of solar insolation are identical in both cases, case 1 also requires a larger PV array (see METHODS section) to support the increased hydrogen production requirement. It is expected that case 1 will be more capital cost intensive than case 2, due to the fact that a larger hydrogen storage tank and larger PV array would cost more to implement than the added battery storage capacity.

Depending on what time of year the start-up of the ISHES system occurs, the hydrogen tank should be initially charged with the amount of hydrogen found in Figures 1 or 2 that corresponds to that particular time of year. The optimized storage tank values of maximum pressure and storage volume ensure that the tank is never completely empty, and rarely completely full to account for expected variation in weather conditions. Starting up the ISHES with a different value than what is found in Figure 1 or 2 will perturb this balance. Starting with more hydrogen than necessary will not cause system downtime, however the system will be overdesigned and will not utilize the full potential of each system component. Starting with less hydrogen than depicted will eventually cause system downtime during the winter season.

In principle, other methods of hydrogen storage (i.e. in the form of metal hydrides) could be used in ISHES and potentially lower the cost of the storage component. It is evident that the relative amount of hydrogen stored will essentially remain the same, therefore, for the purpose of system performance optimization, the method of hydrogen storage is not essential. This issue will become important during cost optimization of the ISHES. The same holds true for an addition of an oxygen storage sub-system to the ISHES. Storing oxygen produced by the electrolyzer for use in the fuel cell (rather than ambient air) could potentially increase the overall cost of the system. However, since the use of oxygen affects the efficiency, and consequently size and cost of the fuel cell, the added cost of oxygen storage will have to be weighed against the reduced cost of the fuel cell.

CONCLUSIONS

TRNSYS was chosen as a viable platform for performing simulations on the proposed ISHES. The main components of the energy system are a photovoltaic array, PEM electrolyzer, PEM fuel cell, battery, pressurized hydrogen storage unit, controller, and electric load. The simulation code was customized in order to model the specific characteristics of proposed system components. A realistic load profile was chosen as an example application for the renewable energy produced by the ISHES system, and system components have been designed and optimized to meet this load with zero percent system downtime. Results from simulations of two cases, one with four batteries and one with twelve batteries, show that a system with fewer batteries and, therefore one that is more renewable, requires a larger PV array to supply necessary power, and may be more costly. The details of this cost analysis, along with the potential to store oxygen produced by the electrolyzer and the use of metal hydrides to store hydrogen, have been left until a system cost optimization is conducted.

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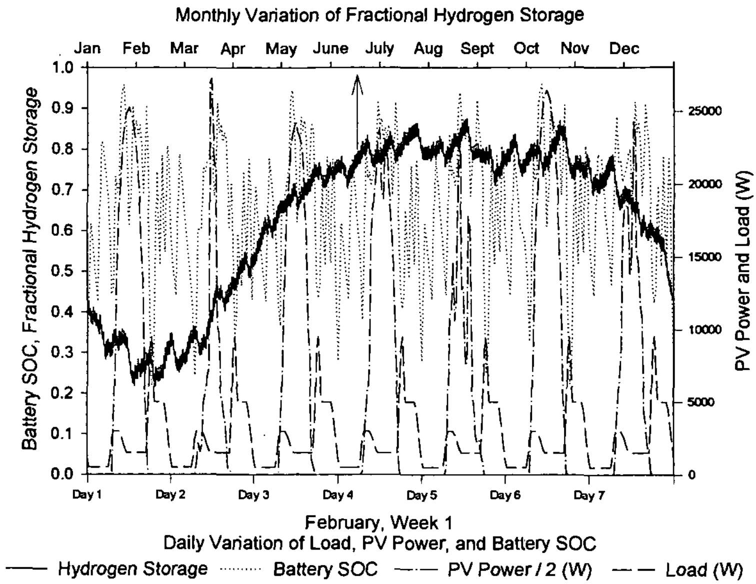

Figure 1: Case 1 Simulation Results

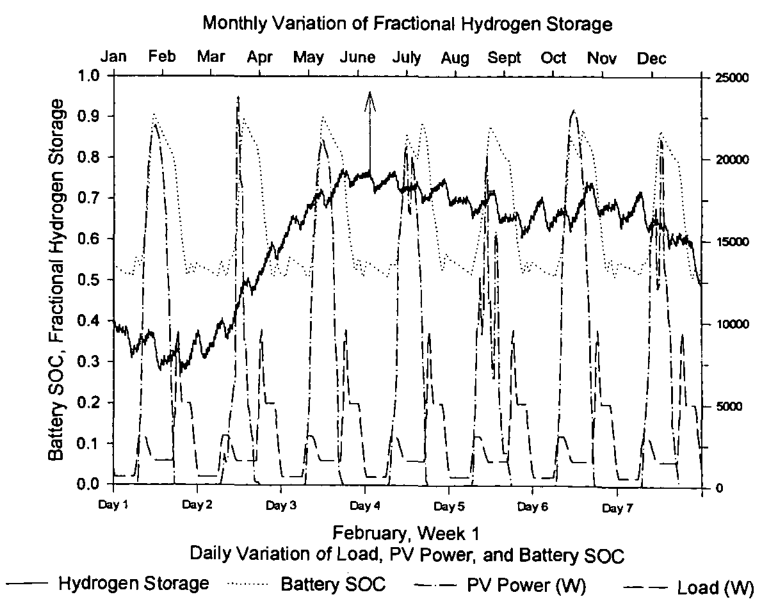

Figure 2: Case 2 Simulation Results